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Development of an integrated methodology for the energy needs of a major urban city: The case study of Athens, Greece

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ABSTRACT

In the present paper a Linear Programming (LP) methodology for the city of Athens, Attica region is implemented trying to identify the energy supply levels based on the energy use, aiming to determine the optimal way for the energy needs to be covered. The final aim was to find the best solution/s to meet the (metropolitan) city's energy needs using Renewable Energy Sources (RES) and additionally implement a techno-economic analysis through a developed tool, in order to find which RES should participate in the city's energy system examining different scenarios focusing not only on the projects' economical success but also on minimizing the cost for the society.

Contents

1. Introduction

Greece has come down to a crucial weakness point regarding energy management. The situation is more serious in highly populated areas with significantly higher electricity and heating consumption needs. The current distribution plan for the installation of RES in Greece is definitely an obstacle for greening Athens. The main outcome of the paper – based on the linear programming (LP) approach – was not only to define the optimal way to meet the city's (urban area of Athens extends far beyond the administrative municipal city limits) energy requirements using dispensable renewables, but at the same time to allocate the source and for which end use.

The under examination methodology proposes an alternative plan for setting a viable urban energy plan and it can contribute in satisfying the need of Greece to cover 20% of its electric energy needs from renewables up to 2020 [1]. Since half of the Greek population resides in the Attica region, by proposing a viable solution for a huge problem like the city's energetic problem, Athens not only can develop itself in a sustainable way but also the rest of the country could develop without the constraints of the "hydrocephalusly" developed city of Athens. The energy characteristics of the Attika region were analyzed, and the optimal "path" for covering the region's energy needs (aiming to minimize the cost and the efficiency) was identified. This review comprises five sections. Section 2 draws on knowledge gained so far from other studies, Section 3 describes the methodology, Section 4 focuses on scenario

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Nomenclature

A	depreciation
$AEPnet$	net annual energy production (MWh)
C_i	installed capacity of the under examination res projects (mw)
CDR	capital discount rate
CV_{coef}	conversion coefficient in current values ratio
$CVFCF$	current value final cash flow
D_m	deduction
E_q	other electrical electronic/mechanical equipment costs
$FNCF$	final net cash flow
FNI	cumulative cash flow
i	interest
I	interest of the loan
IC	investment cost
$Inst$	installments
IRR	internal rate of return
l	cable length (km)
L	loan
M	maintenance costs
NPV	net present value
NI	net income (or net cash flow)
NRA	net repayment amounts
OC	total operating costs
OCF	operating cash flow
PO	personnel operational costs
$P_{a\text{-}tax}$	profits after-taxes
$P_{p\text{-}tax}$	before tax earnings
T_0	turnover (revenues)
UV	unamortized value
V	land lease, administration costs, unexpected expenses or other additional costs
RES_{Ins}	insurance of renewable energy systems

planning and implementation and shows the results and Section 5 summarizes.

2. Literature review

Over the last few decades a large body of literature has emerged on the applications of various optimization scenarios of the energy industry. Studies were done on how to use energy optimally in several countries or areas [2–7]. A number of papers seem to be focused on how to increase the penetration of RES [8–10] and energy optimization scenarios within the future carbon-free energy industry [11–14].

Although a lot of studies have been carried out in the last few years focusing mainly on the optimization of electricity markets new field, limited papers have appeared on the optimization of resource planning. Brand and Zingerle [15] have published their research for a few countries in Northern Africa studying the influence of RES integration into each country's power system. Mazhari et al. [16] studied system stability proposing a new optimization agent-based methodology aiming on the most economical mixture of solar generation and storage minimizing the risks from high fluctuating demands and unpredictable weather conditions. Barton and Gammon [17] have pointed out the importance of hydrogen production from RES and its need in the future power system, Brouwer [18] stressed the role of fuel cells and hydrogen as well, while Lund et al. have worked much on the role of district heating in RES in the energy systems [19]. Azzopardi and Mutale optimized the integration of PVs into the power systems. Actually, the calculation methodology showed that low efficient modules drop the electricity costs for the end-user, compared to more recent and more efficient PV systems [20]. Koo et al. [21] and Kim et al. [22] worked with different cost and uncertainty scenarios which may have effects on the competitiveness of South Korea's national renewables plan.

Limited research has been done on the optimization of cities' energy resource exploitation planning. Dong et al. [23] presented an innovative methodology for the energy systems planning of Beijing. Østergaard [24] did some research on the optimal design of an energy system in terms of achieving the optimal integration of fluctuating energy sources. Deshmukh and Deshmukh [25] implemented a multi-criteria analysis for supporting the municipal energy system planning by means of generating plans for the optimal energy allocation among final customers in the region. Cai et al. [26,27] presented a large scale model for optimizing long term planning in the Waterloo region.

However, it seems that there is significant space for research on optimal resource planning which can identify the remaining space for RES development for greening the energy system within a city and also review the proposed results from a techno-economic analysis point of view.

3. Proposed methodology

The model proposed under this research was developed to solve and customize the much needed green energy in the wider area of the city of Athens aiming at an urban viable energy system. For the exploitation of solar energy thermal solar energy systems (solar radiation in heat) and photovoltaic systems were used. Other RESs available in the city's wider area were geothermal energy, wind energy, energy recovery from MSW and biomass units.

The ultimate aim was to maximize the outcome of the objective function based on the "efficiency-to-cost" ratio. Using a deterministic approach examining several models and LP (lindo tool [28]), based on the designed model the initial optimal solution was provided. Under the optimal solution, further analysis was done examining various deterministic scenarios modifying the availability of each source in order to examine how the system reacts on these changes.

The RES model sets various end uses (categorized and data taken from Public Power Corporation [29]) such as domestic use (DU), industrial use (IU), commercial use (CU), agricultural use (AU), public use (PU) and lighting of roads and squares (LRS). Data were received from the Public Power Corporation (PPC) for the years 2003–2009 [30].

In the study it is shown that efficiency and cost are the most important factors in the use of RESs. For each energy source available the average unit costs (per produced kiloWatt-hour) were chosen mainly from the literature. However, because of the author's prior experience in working in Greece with several developers and utilities the data were double-checked for their validity and credibility. Concerning the efficiency however, an average efficiency was chosen for different sources of energy but for the same system. Also, it should be noted that RES systems were proposed in the model to meet the electrical needs and not to cover other kind of needs (e.g. heating needs or hot water, etc.).

Therefore, the average efficiency or the Capacity Factor (CF) of a wind farm in the Attica region, where medium and high winds prevail, will be relatively high compared to a farm in Western Greece where proper sites for wind farm development are hard to be found [31]. Also, the levels of solar irradiation are higher than any site for instance in Northern Greece, where average daily sunlight is less intense [32,33]. The projects' (wind and PV projects mainly) applications in the Attica region can be seen online from the Geographical Informational System (GIS) online tool for the projects submitted for authorization from the Regulatory Authority for Energy (RAE) (Fig. 1) [33].

Table 1 shows the unit costs from each energy source [€/produced kW h] used in the optimization model.

In general, efficiencies vary on the examined areas. However, as this research is focused on the city of Athens and in the wider built environment of the Attica region, average capacity factors and therefore efficiencies of units were taken, based not only on the existing units, but also on the development perspectives of each resource. In particular, solar thermal conversion collectors' efficiency was taken as 38.5%, while for a PV park it was considered 13% and for solar concentrators 28% [34,49,50]. Efficiency for biomass units was taken to be 60%, however, it should be noted, that it is most of the times linked with the energy mixture [42,51]. Geothermal unit efficiency is taken to be around 80% [52–54]. The average onshore and offshore wind farms' CF was considered 32% [46,55–57] and the CF of a hydropower unit was assumed to be 34% (however, in this model, for Athens, it is not used, as hydro [58–60]). The efficiency of Waste-to-Energy (energy recovered from MSW) was taken as 29% [61,62].

The reliability coefficients of each renewable system used in the optimization were also foreseen. These coefficients state the availability of each system for a reliable power supply and were used in the model as constraints. The coefficients are: 0.1 per 10,000 h for solar systems, 0.9 at 10,000 h for biomass and geothermal energy systems, and 0.5 per 10,000 h for wind [63–65]. Data for quantities of wastes produced in Athens and electricity consumption in the region were taken from Refs. [66–69]. The variables used are shown in the Appendix (Table A4).

Fig. 1. Online tool for project applications for license in the Attica region.

Table 1
Unit costs taken for each energy source [€/kWh].

RES	[€/kWh]	Reference
Solar collectors	0.0453	[34,35]
PV	0.2	[34,36]
Concentrated solar power (CSP)	0.125	[37,38]
Wind energy	0.038	[39–41]
Biomass	0.08	[42,43]
Geothermal energy	0.106	[44]
Hydro energy	0.045	[45,46]
Energy recovery from MSW	0.04	[47,48]

Variables X_1–X_{44} represent the percentage of the utilization of each energy system and are shown in Table A4. The coefficients in front of the variables in the model came from the representation for each unit of the "efficiency/cost" ratio. The proposed methodology was implemented only trying to indentify the best solution for the electricity demand of the Attica region and the replacement of traditional units was not studied under this research. After determining each resource's contribution rate to the optimal solution, a techno-economic analysis was implemented in order to evaluate the solution every time [70]. Also, an important assumption made in this research should be pointed out, that RES can cover only up to 45% of the region's electricity needs. The obtained results strongly depend on the assumptions made here. Also, it should be pointed out that it is not within the purposes of this optimization methodology to examine energy storage tools or demand side management for examining further RES penetration into the grid. Large hydro plants, fossil fuels (lignite) and conventional plants are usually assumed to supply the remaining 55% of the city's major energy needs [1, 71].

A stochastic approach could examine the correspondence of the utilization rate of each RES in the system. The scenarios examined each time affect the whole RES system, in the sense of availability of each system. For instance, when one RES is not in a position to contribute at its highest potential for various reasons (e.g. weather conditions or fluctuating demands, etc.), other sources automatically cover this system default. The generic applicable representation of the model is given as

$$Max\left(A_j\sum_{i=1}^{2}X_i+B_j\sum_{i=3}^{8}X_i+E_j\sum_{i=9}^{14}X_i+F_j\sum_{i=15}^{20}X_i+D_j\sum_{i=21}^{26}X_i + C_j\sum_{i=27}^{32}X_i+G_j\sum_{i=33}^{38}X_i+H_j\sum_{i=39}^{44}X_i\right) \tag{1}$$

which is subject to:

$$\sum_{i=1}^{2}X_i \le R_1, \tag{2}$$

$$\sum_{i=3}^{8}X_i \le R_2, \tag{3}$$

$$\sum_{i=9}^{14}X_i \le R_3, \tag{4}$$

$$\sum_{i=15}^{20}X_i \le R_4, \tag{5}$$

$$\sum_{i=21}^{26}X_i \le R_5, \tag{6}$$

$$\sum_{i=27}^{32}X_i \le R_6, \tag{7}$$

$$\sum_{i=33}^{38}X_i \le R_7, \tag{8}$$

$$\sum_{i=39}^{44}X_i \le R_8, \tag{9}$$

$$X_1+X_3+X_9+X_{15}+X_{21}+X_{27}+X_{33}+X_{39} \le R_9, \quad (10)$$

$$X_2+X_6+X_{12}+X_{18}+X_{24}+X_{30}+X_{36}+X_{42} \le R_{10}, \quad (11)$$

$$X_4+X_{10}+X_{16}+X_{22}+X_{28}+X_{34}+X_{40} \le R_{11}, \quad (12)$$

$$X_5+X_{11}+X_{17}+X_{23}+X_{29}+X_{35}+X_{41} \le R_{12}, \quad (13)$$

$$X_7+X_{13}+X_{19}+X_{25}+X_{31}+X_{37}+X_{43} \le R_{13}, \quad (14)$$

$$X_8+X_{14}+X_{20}+X_{26}+X_{32}+X_{38}+X_{44} \le R_{14}, \quad (15)$$

$$10\sum_{i=1}^{2} X_i \le R_1, \quad (16)$$

$$10\sum_{i=3}^{8} X_i \le R_2, \quad (17)$$

$$5\sum_{i=9}^{14} X_i \le R_3, \quad (18)$$

$$10\sum_{i=15}^{20} X_i \le R_4, \quad (19)$$

$$2\sum_{i=21}^{26} X_i \le R_5, \quad (20)$$

$$10\sum_{i=27}^{32} X_i \le R_6, \quad (21)$$

$$1.5\sum_{i=33}^{38} X_i \le R_7, \quad (22)$$

$$5\sum_{i=39}^{44} X_i \le R_8, \quad (23)$$

$$\sum_{i=1}^{44} X_i \ge 0 \quad (24)$$

Applying (a) the average efficiency of each renewable energy source unit shown on Table 2, (b) the restrictions regarding the availability of each source and (c) the energy needs of the city of Athens, the model can be clearly particularized. To fill the gap generated by the lack of one RES in the RES system, the correspondence of RES is quantified. Table 3 shows the efficiency coefficients.

Each RES can cover up to 45% of the electric demand of the area {constraints (2)–(9)}. An upper limit is set in the mathematical model for each region and for each end-use, based on the demand and consumption data taken from the Public Power Corporation (PPC) [69] {constraints (10)–(15)}. As mentioned before, the reliability coefficients 0.1 at 10,000 h for solar systems, 0.5 at 10,000 h for wind and 0.9 at 10,000 h for biomass and geothermal energy systems, were also used in the model [62–64] {constraints (16)–(23)} and finally the non-negativity represented with constraint (24). ConstantsR_i, i=1–14, represent the amount of energy each RES can cover in the region (R_1–R_8) and the amount of energy each defined end-use needs (constants R_9–R_{14}) (Table 4). The energy demand up to which each RES can contribute in the region was taken based on the RES project applications in the wider area of Athens [33] and the amount of energy each end-use needs was obtained from the PPC files [69].

Table 2
Units' efficiency or CF assumed for different energy sources [%] [43].

RES	[%]	Reference
Solar collectors	38.5	[34,49,50]
PV	13	[34,49,50]
Concentrated solar power (CSP)	28	[34,49,50]
Biomass	60	[42,51]
Geothermal energy	80	[52–54]
Wind energy	32	[46,55–57]
Hydro energy	34	[58–60]
Energy recovery from MSW	29	[61,62]

Table 3
Efficiency coefficients per each RES [%].

Source of energy	[%]	Coefficient	Coefficient symbol
Solar collectors	A	A/0.0453	Aj
PV	B	B/0.2	Bj
Concentrated solar power (CSP)	C	C/0.125	Cj
Wind energy	D	D/0.038	Dj
Biomass	E	E/0.08	Ej
Geothermal energy	F	F/0.106	Fj
Hydro energy	G	G/0.045	Gj
Energy recovery from MSW	H	H/0.04	Hj

Table 4
Constants *Ri* used in the model.

Constants R_i	[%]	Constants R_i	[%]
R_1	5.70	R_8	11.10
R_2	15.00	R_9	45.25
R_3	10.00	R_{10}	0.47
R_4	0.35	R_{11}	32.81
R_5	100.00	R_{12}	16.71
R_6	15.00	R_{13}	3.45
R_7	0.00	R_{14}	1.41

4. Results and cash flow analysis

4.1. Preliminary results

A detailed optimal allocation for RES is found for the region by solving the mathematical model. In specific, the proper RES for each end-use was found. The percentages in the results in the model correspond to the consumption in the region based on the data obtained from PPC [70]. The optimal allocation is shown below in Fig. 2. It is obvious that in the Athens region, this 45% of their electricity needs cannot be covered economically and efficiently.

As already mentioned, through an extensive analysis the response of the system was quantified in various cases. Energy safety in delivery for the most crowded and commercial urban area in Greece was of absolute importance in this research. Through a techno-economic analysis (using economic principles for designing more efficient units) which takes into account the minimization of the costs (operational costs, maintenance, land use costs, etc.) the city population, distances from the Waste-to-Energy units, etc., the optimal planning of these units is being optimized. The results show that, on the lack of collectors contribution nothing actually is happening, for CSP and PV or Biomass this percent is 25% (note that 26.02% is the optimal distribution), while when Wind is not contributing at all, only up to 3.5% can be covered. This means that the RES development in Athens is apparently exclusively based on the wind development potentials. A detailed presentation of the results in all RES variations is shown in Appendix (Table A1). The energy

(in MWh) needed from each system (and for each end-use) under the optimal solution is shown in Table 5. A preliminary estimation shows the needed power for each RES to be installed.

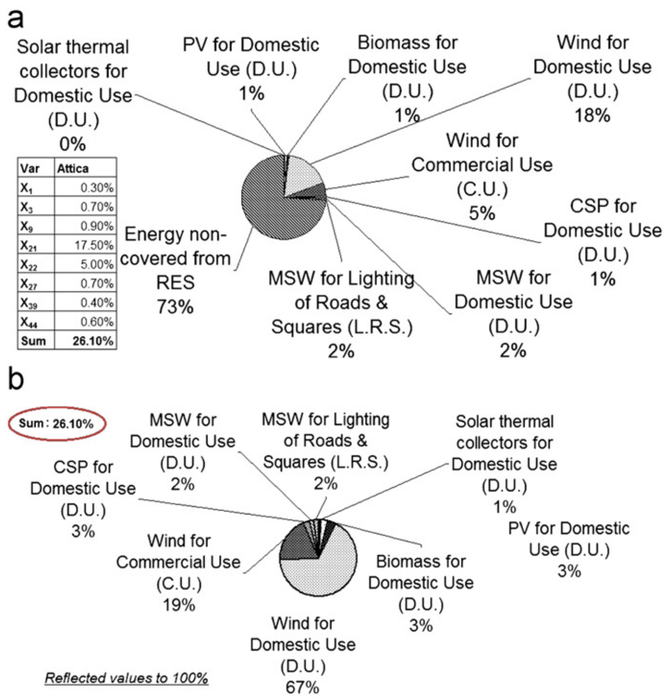

Fig. 2. RES contribution in the region of Athens.

Table 5
Energy needed from each RES system (optimal solution).

Variables	[MWh]	[MW]
Solar thermal collectors for domestic use (D.U.)	46,872.6	13.90
PV for domestic use (D.U.)	123,349.0	108.32
Biomass for domestic use (D.U.)	164,465.3	31.29
Geothermal for domestic use (D.U.)	2878.1	0.41
Wind for domestic use (D.U.)	3,193,505.8	1466.76
Wind for commercial use (C.U.)	918,127.8	
CSP for domestic use (D.U.)	123,349.0	50.29
Energy recovery from MSW for domestic use (D.U.)	66,608.5	71.86
Energy recovery from MSW for lighting of roads & squares (L.R.S.)	115,948.1	
Sum	4,755,104.4	1742.83

The results for the optimal solution are: 13.9 MW of collectors, 108.3 MW PVs, 31.29 MW of biomass units, 410 KW of geothermal units, 1466.7 MW of wind farms, approximately 50 MW of CSP units and 71.86 MW of energy recovery from MSW units.

4.2. Cash flow model: Examined scenarios

For these 1742.83 MW (and 4,755,104.4 MWh) needed to cover approximately 26% of the energy needs of Athens, an average investment analysis for the whole system could be done based on the current legislative support schemes (Law 3851/2010 “Accelerating the development of Renewable Energy Sources to deal with climate change and other regulations addressing issues under the authority of the Ministry of Environment, Energy and Climate Change”) [1].

Based on the data for the projects under development in Athens, Attica region, we have (a) 103 MW of PV, (b) 7.5 MW of biomass and (c) 716 MW of Wind farms submitted to the authorities for obtaining permits. Therefore, setting energy availability as a basic decision-making criterion, the selected scenarios to be examined are going to be (a) the optimal solution (which is participation for all RES at 100%), (b) the PV participation up to 90% (selectively, only because the aggregation of the under development projects is 103.56 MW and not the 108.3 we need), (c) biomass participation up to 20% since only one unit of an approximate capacity of 7.3 MW covers sufficiently 20% of the 31 MW we need, (d) MSW 0% participation and (e) scenarios 40%–90% of wind participation since the projects under development for the Attica region are in total 715 MW, which is almost half of what is needed based on the optimal solution. Based on the scenarios list the range of the MWs proposed to be installed is from 862.83–1810.57 (scenarios in Table A2, Appendix). However, apart from these scenarios, and just because Athens and the wider Attica region would definitely have significant issues in planning such a large number of wind turbines onshore, three different offshore scenarios were examined as well: (I) *OptWFOff0.4*, (II) *OptWFOff0.6* and (III) *OptWFOff0.8*. *OptWFOff0.4* is the scenario in which, out of the sum of the wind farms needed to be installed in the Attica region, 40% should be installed offshore, *OptWFOff0.6* means 60% of those should be installed offshore, and finally *OptWFOff0.8* represents the scenario in which 80% of those should be installed offshore (Table A3, Appendix).

An excel-based investment analysis model was developed (Appendix B, Fig. B1 and list of various assumptions on the examined scenarios) which takes into consideration the available subsidization from the Greek government (paid by the taxpayers) for the implementation of new projects for each RES. The ultimate

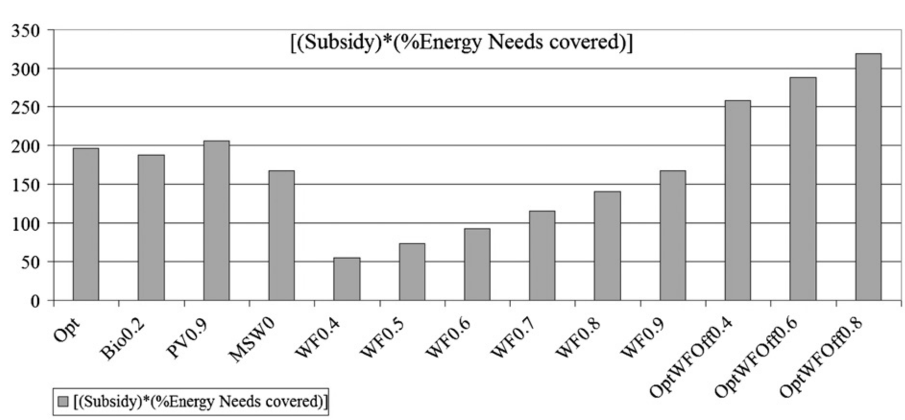

Fig. 3. Performance Indicator [(Subsidy)*(%Energy Needs covered)] for the examined systems.

aim was to select not only the solution with the minimum cost for the society (minimum subsidy) but at the same time to contribute as much as possible from the energy needs of the Attica region, as shown from the optimization methodology.

The turnover (revenues) T_0 for 20 years of the proposed system are:

$$\sum_{yr=1}^{yr=20} T_0 = \text{FiT}\ AEPnet, \tag{25}$$

where FiT, the feed-in-tariff, policy is updated annually.

Based on the existing legislation, 3% before V.A.T. is deducted going to household consumers, to a special fund and to local municipalities. This total 3% deduction Dm is defined as

$$\sum_{yr=1}^{yr=20} Dm = 3\% \sum_{yr=1}^{yr=20} T_0 \tag{26}$$

Other major costs are Personnel Operational Costs, PO, Maintenance Costs, M, Insurance of RES system, RES_{Ins}, other electrical electronic/mechanical Equipment costs, Eq, land leases, administration costs, unexpected expenses or other additional costs, V. Therefore, the total Operating Costs, OC, are

$$\sum_{yr=1}^{yr=20} OC = \sum_{yr=1}^{yr=20} D_m + \sum_{yr=1}^{yr=20} PO + \sum_{yr=1}^{yr=20} M + \sum_{yr=1}^{yr=20} RES_{Ins}$$

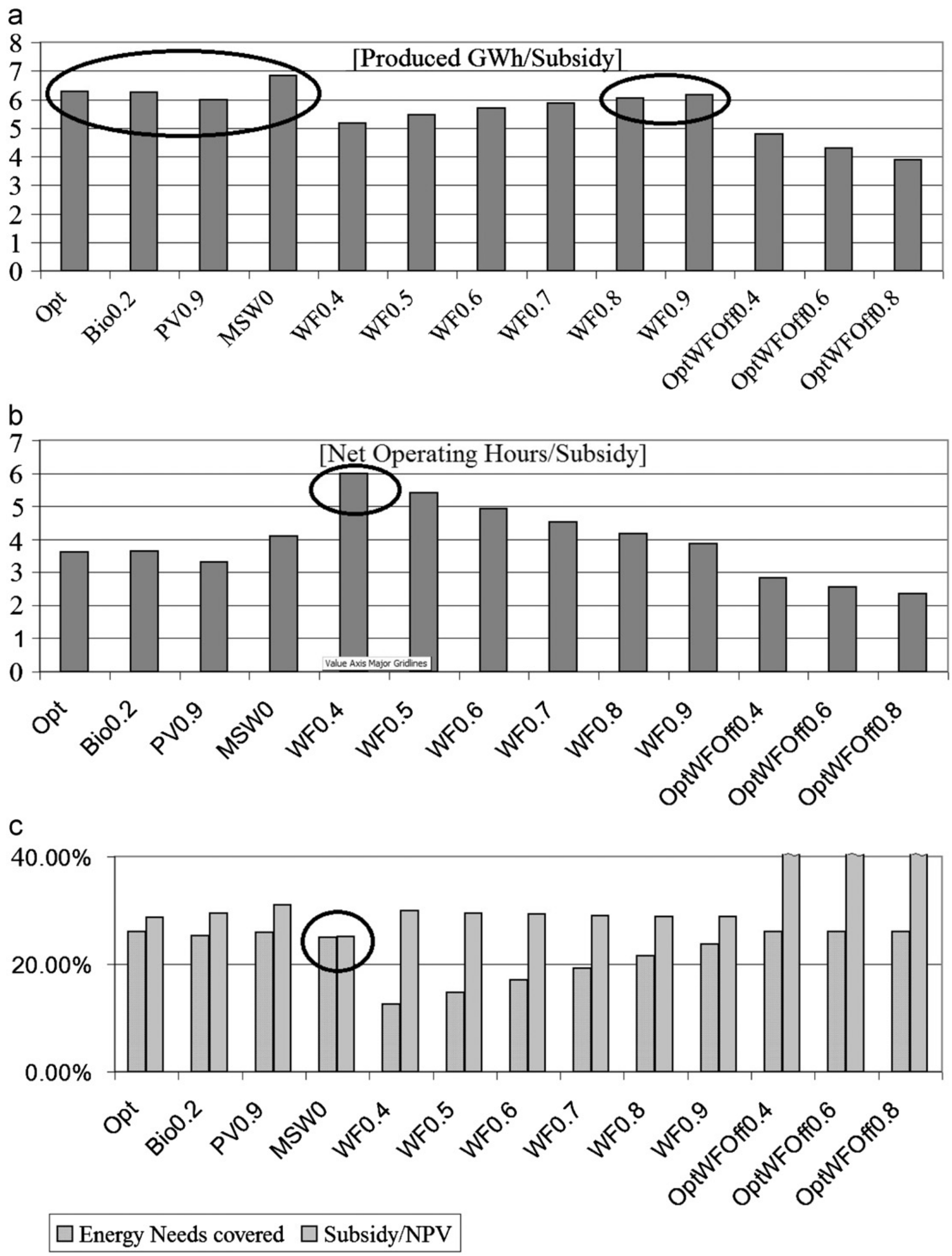

Fig. 4. Performance Indicators of the examined systems.

$$+\sum_{yr=1}^{yr=20} Eq+\sum_{yr=1}^{yr=20} V, \tag{27}$$

where PO are the salaries for the permanent employees of the RES system during operation period (20 years were taken as a reference lifetime for the system since 90% of the investment is WFs and PV parks), M the required extension cost to be paid to the energy systems manufacturers (fixed price most of the times per MW) in order the service to be undertaken from them, and RES_{Ins} a standard percentage based on the RES total investment initial cost.

The proposed financial plan usually for a project in Athens is equity: 25%, loan: 55% (full repayment period is set to be 10 years, with a standard sinking fund and depending on the market rules a loan interest could be between 6%–7%), and subsidy: 20%, not for Large Enterprizes (LEs) within the Attica region. It is necessary however, for the proposed financial scheme to cover the minimum requirements in equity capitals set by the development law of 25% [72].

Regarding the Operating Cash Flow, *OCF*:

$$\sum_{yr=1}^{yr=20} OCF=\sum_{yr=1}^{yr=20} T_0-\sum_{yr=1}^{yr=20} OC \tag{28}$$

Taking into consideration that usually a private equity and debt ought to be fully be paid off (depending on the subsidization) a 60%–70% of the total Investment Cost, *IC*, is the participation rate out of all. Therefore for the Unamortized Value, *UV*:

$$\sum_{yr=1}^{yr=20} UV=ICa,\ where\ 0.6\leq a\leq 0.7. \tag{29}$$

The Depreciation, *A*, can be estimated using the formula

$$\sum_{yr=1}^{yr=20} A=15\%\sum_{yr=1}^{yr=20} UV, \tag{30}$$

where 15% is the percentage used for the depreciation declining–balance method.

After calculating the payment amount (Installments *Inst*) on the loan, *L*, (with a rate of interest, *i*), following the formula

$$\sum_{yr=1}^{yr=10} Inst=\sum_{yr=1}^{yr=10} (Li)/[1-(1+i)]^{-N}, \tag{31}$$

where *N* equals 10. *N* is the number of years of repayment, and after calculating the interest of the loan *I*:

$$\sum_{yr=1}^{yr=20} I=i\sum_{yr=1}^{yr=20} L, \tag{32}$$

the calculations are updated on a yearly basis, based on the loan balance update. Therefore, Before Tax Earnings, $P_{p\text{-}tax}$, are given from

$$\sum_{yr=1}^{yr=20} P_{p-tax}=\sum_{yr=1}^{yr=20} OCF-\sum_{yr=1}^{yr=20} A-\sum_{yr=1}^{yr=10} I \tag{33}$$

Also, knowing that the taxes for RES investments are 25% the final results (profits after-taxes, $P_{a\text{-}tax}$) can be estimated by removing the taxes from $P_{p\text{-}tax}$. This way Net Income (or Net Cash Flow) *NI* is equal to

$$\sum_{yr=1}^{yr=20} NI=\sum_{yr=1}^{yr=20} P_{a-tax}+\sum_{yr=1}^{yr=20} A, \tag{34}$$

and Final Net Cash Flow, *FNCF*:

$$\sum_{yr=1}^{yr=20} FNCF=\sum_{yr=1}^{yr=20} NI-\sum_{yr=1}^{yr=20} NRA, \tag{35}$$

where *NRA* is the Net Repayment Amount. Calculating the Cumulative Cash Flow (*FNI*, adding up for all 20 years) and the conversion coefficient in current values ratio, CV_{coef}, using the formula

$$CV_{coef}=\frac{1}{(1+CDR)^{yr}}, \tag{36}$$

where *CDR* is the Capital Discount Rate and *yr* each year; the Current Value Final Cash Flow, *CVFCF*, can be calculated from

$$\sum_{yr=1}^{yr=20} CVFCF=\sum_{yr=1}^{yr=20} CV_{coef}FNCF, \tag{37}$$

which gives us the Net Present Value (NPV), the project repayment period (when the cash flow turns to positive), the Cumulative Revenues and finally the Project IRR. The project IRR is the discount rate that makes the NPV of all cash flows of the project equal to zero.

Based on the optimization results and the updated estimates of power plant capital and operating costs taken from EIA [73], several scenarios were examined and the economic results for all the scenarios are shown on Table A3, Appendix.

Several indicators can compare economically different scenarios examined for the RES development strategy on the region and assist decision makers to optimize planning. It can be seen from Table A3 (Appendix) that the highest project IRR factor can be achieved in the *MSW0* scenario, however it does not offer the highest number of net operating hours and therefore produced energy (in MWh) to the system. Figs. 3 and 4 show the relation between proposed systems and indicators introduced like [(Subsidy)*(%Energy Needs covered)], [Produced GWh/Project Cost], [Net Operating Hours/Subsidy], and [Subsidy/NPV].

It is understood that the indicator [(Subsidy)*(%Energy Needs covered)] shows the economic efficiency of the state subsidization (which is covered from the taxpayers). In reality it is an indicator that presents how much money should be spent to each scenario in correlation to the energy needs covered. It is obvious that the offshore scenarios (*OptWFOff0.4*, *OptWFOff0.6* and *OptWFOff0.8*) are significantly expensive. It is seen, however, that *WF0.9* is the best "value for money" case, with *MSW0* to follow.

For the indicators [Produced GWh/Subsidy] and [Net Operating Hours/Subsidy] we need the fraction to be the greatest possible. Therefore, there is need in both cases to have the greater numerator and lesser denominator. *MSW0* seems the most optimal scenario and *Opt*, *WF0.9*, *Bio0.2*, and *WF0.8* could be chosen (diagram a). For diagram (b) it is obvious that *WF0.4* is the best solution, however we know that options *WF0.4*–*WF0.8* cover less than 22%, while *MSW0* covers more than 25%. In diagram (c) of Fig. 4, [Subsidy/NPV], it can be observed that we want the opposite, meaning the smaller fraction. It can be seen that despite the fact that with the Opt and offshore (*OptWFOff0.4*, *OptWFOff0.6* and *OptWFOff0.8*) scenarios all needs are covered, their cost is higher than the *MSW0* scenario which covers only 1% less and costs to the taxpayers (for the subsidy) at least 110 MEUR less. Regarding NPV, *MSW0* has the best results out of all the examined scenarios, and this way *MSW0* solution could be considered as a win–win situation for both social welfare (minimizing the subsidization) and companies willing to be involved in the planning of such a huge project.

Table A1
Renewable energy distribution model by varying deterministically (by 10% each time) all available renewable potentials.

	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	Optimal
Collectors' variation [%]											
Solar thermal collectors for domestic use (D.U.)	0.000	0.045	0.045	0.090	0.090	0.135	0.135	0.180	0.225	0.225	0.270
PV for domestic use (D.U.)	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675
Biomass for domestic use (D.U.)	0.900	0.900	0.900	0.900	0.900	0.900	0.900	0.900	0.900	0.900	0.900
Wind for domestic use (D.U.)	17.730	17.685	17.685	17.640	17.640	17.595	17.595	17.550	17.505	17.505	17.460
Wind for commercial use (C.U.)	4.770	4.815	4.815	4.860	4.860	4.905	4.905	4.950	4.995	4.995	5.040
CSP for domestic use (D.U.)	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675
Energy recovery from MSW for domestic use (D.U.)	0.360	0.360	0.360	0.360	0.360	0.360	0.360	0.360	0.360	0.360	0.360
Energy recovery from MSW for lighting of roads & squares (L.R.S.)	0.630	0.630	0.630	0.630	0.630	0.630	0.630	0.630	0.630	0.630	0.630
Sum	25.785	25.785	25.830	25.830	25.875	25.875	25.920	25.965	25.965	26.010	26.010
Biomass variation											
Solar thermal collectors for domestic use (D.U.)	0.257	0.257	0.257	0.257	0.257	0.257	0.257	0.257	0.257	0.257	0.257
PV for domestic use (D.U.)	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675
Biomass for domestic use (D.U.)	0.000	0.090	0.180	0.270	0.360	0.450	0.540	0.630	0.720	0.810	0.900
Geothermal for domestic use (D.U.)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.016
Geothermal for lighting of roads & squares (L.R.S.)	0.016	0.018	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.000
Wind for domestic use (D.U.)	18.376	18.288	18.196	18.106	18.016	17.926	17.836	17.746	17.656	17.566	17.476
Wind for commercial use (C.U.)	4.124	4.217	4.304	4.394	4.484	4.574	4.664	4.754	4.844	4.934	5.024
CSP for domestic use (D.U.)	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675
Energy recovery from MSW for domestic use (D.U.)	0.380	0.383	0.380	0.380	0.380	0.380	0.380	0.380	0.380	0.380	0.365
Energy recovery from MSW for lighting of roads & squares (L.R.S.)	0.619	0.621	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.635
Sum	25.121	25.214	25.301	25.391	25.481	25.571	25.661	25.751	25.841	25.931	26.021
Wind variation											
Solar thermal collectors for domestic use (D.U.)	0.257	0.257	0.257	0.257	0.257	0.257	0.257	0.257	0.257	0.257	0.257
PV for domestic use (D.U.)	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.153	0.000	0.675
PV for industrial use (I.U.)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.527	0.675	0.000
Biomass for domestic use (D.U.)	0.900	0.900	0.900	0.900	0.900	0.900	0.900	0.900	0.900	0.000	0.900
Biomass for industrial use (I.U.)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.900	0.000
Geothermal for domestic use (D.U.)	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018
Wind for domestic use (D.U.)	0.000	2.250	4.500	6.750	9.000	11.250	13.500	15.750	18.000	19.728	17.478
Wind for commercial use (C.U.)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	5.027
Wind for public use (P.U.)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.527	0.000
CSP for domestic use (D.U.)	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.000	0.675
CSP for public use (P.U.)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.675	0.000
CSP for lighting of roads & squares (L.R.S.)	0.635	0.635	0.635	0.635	0.635	0.635	0.635	0.635	0.635	0.000	0.000
Energy recovery from MSW for domestic use (D.U.)	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.365	0.365
Energy recovery from MSW for lighting of roads & squares (L.R.S.)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.635	0.635
Sum	0.000	5.774	8.021	10.271	12.521	14.771	17.021	19.271	21.521	23.771	26.021
CSP variation											
Solar thermal collectors for domestic use (D.U.)	0.257	0.257	0.257	0.257	0.257	0.257	0.257	0.257	0.257	0.257	0.257
PV for domestic use (D.U.)	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675
Biomass for domestic use (D.U.)	0.284	0.351	0.419	0.486	0.554	0.621	0.689	0.756	0.824	0.891	0.900
Biomass for lighting of roads & squares (L.R.S.)	0.621	0.554	0.486	0.419	0.351	0.284	0.216	0.149	0.081	0.014	0.000
Geothermal for domestic use (D.U.)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.018
Geothermal for lighting of roads & squares (L.R.S.)	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.000
Wind for domestic use (D.U.)	18.153	18.086	18.018	17.951	17.883	17.816	17.748	17.681	17.613	17.546	17.478
Wind for commercial use (C.U.)	4.352	4.419	4.487	4.554	4.622	4.689	4.757	4.824	4.892	4.959	5.027
CSP for domestic use (D.U.)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.675
CSP for lighting of roads & squares (L.R.S.)	0.000	0.068	0.135	0.203	0.270	0.338	0.405	0.473	0.540	0.608	0.000
Energy recovery from MSW for domestic use (D.U.)	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.365
Energy recovery from MSW for lighting of roads & squares (L.R.S.)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.635
Sum	0.000	25.416	25.481	25.549	25.616	25.684	25.751	25.819	25.886	25.954	26.021
PV variation											
Solar thermal collectors for domestic use (D.U.)	0.257	0.257	0.257	0.257	0.257	0.257	0.257	0.257	0.257	0.257	0.257
Solar thermal collectors for agricultural use (A.U.)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
PV for domestic use (D.U.)	0.000	0.068	0.135	0.203	0.203	0.338	0.405	0.473	0.540	0.608	0.675
Biomass for domestic use (D.U.)	0.284	0.284	0.284	0.284	0.284	0.284	0.284	0.284	0.284	0.284	0.900
Biomass for lighting of roads & squares (L.R.S.)	0.621	0.621	0.621	0.621	0.621	0.621	0.621	0.621	0.621	0.621	0.000
Geothermal for domestic use (D.U.)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.018
Geothermal for lighting of roads & squares (L.R.S.)	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.000
Wind for domestic use (D.U.)	18.153	18.086	18.018	17.951	17.951	17.816	17.748	17.681	17.613	17.546	17.478
Wind for commercial use (C.U.)	4.352	4.419	4.487	4.554	4.554	4.689	4.757	4.824	4.892	4.959	5.027
CSP for domestic use (D.U.)	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675
Energy recovery from MSW for domestic use (D.U.)	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.365
Energy recovery from MSW for lighting of roads & squares (L.R.S.)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.635
Sum	0.000	25.416	25.481	25.549	25.549	25.684	25.751	25.819	25.886	25.954	26.021
Geothermal variation											
Solar thermal collectors for domestic use (D.U.)	0.257	0.257	0.257	0.257	0.257	0.257	0.257	0.257	0.257	0.257	0.257
PV for domestic use (D.U.)	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675
Biomass for domestic use (D.U.)	0.266	0.266	0.270	0.270	0.270	0.275	0.275	0.275	0.279	0.279	0.900
Biomass for lighting of roads & squares (L.R.S.)	0.635	0.635	0.630	0.630	0.630	0.626	0.626	0.626	0.621	0.621	0.000
Geothermal for domestic use (D.U.)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.018

Table A1 (*continued*)

	0%	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**Optimal**
Geothermal for lighting of roads & squares (L.R.S.)	0.000	0.000	0.005	0.005	0.005	0.009	0.009	0.009	0.014	0.014	0.000
Wind for domestic use (D.U.)	17.492	17.492	17.487	17.487	17.487	17.483	17.483	17.483	17.478	17.478	17.478
Wind for commercial use (C.U.)	5.009	5.009	5.013	5.013	5.013	5.018	5.018	5.018	5.022	5.022	5.027
CSP for domestic use (D.U.)	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675
Energy recovery from MSW for domestic use (D.U.)	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.365
Energy recovery from MSW for lighting of roads & squares (L.R.S.)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.635
Sum	0.000	26.006	26.009	26.010	26.012	26.014	26.015	26.017	26.018	26.020	26.021

Table A2
Examined scenarios.

Variables	**Optimal** (%)	***Bio-0.2*** (%)	***PV-0.9*** (%)	***MSW-0*** (%)	***WF-0.4*** (%)	***WF-0.5*** (%)	***WF-0.6*** (%)	***WF-0.7*** (%)	***WF-0.8*** (%)	***WF-0.9*** (%)
Solar thermal collectors for domestic use (D.U.)	*0.26*	*0.26*	*0.26*	*0.26*	*0.26*	*0.26*	*0.26*	*0.26*	*0.26*	*0.26*
PV for domestic use (D.U.)	*0.68*	*0.68*	*0.61*	*0.68*	*0.68*	*0.68*	*0.68*	*0.68*	*0.15*	*0.00*
PV for industrial use (I.U.)	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.53*	*0.68*
Biomass for domestic use (D.U.)	*0.90*	*0.18*	*0.28*	*0.90*	*0.90*	*0.90*	*0.90*	*0.90*	*0.90*	*0.00*
Biomass for industrial use (I.U.)	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.90*
Biomass for lighting of roads & squares (L.R.S.)	*0.00*	*0.00*	*0.62*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
Geothermal for domestic use (D.U.)	*0.02*	*0.00*	*0.00*	*0.02*	*0.02*	*0.02*	*0.02*	*0.02*	*0.02*	*0.02*
Geothermal for lighting of roads & squares (L.R.S.)	*0.00*	*0.02*	*0.02*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
Wind for domestic use (D.U.)	*17.48*	*18.20*	*17.55*	*17.84*	*9.00*	*11.25*	*13.50*	*15.75*	*18.00*	*19.73*
Wind for commercial use (C.U.)	*5.03*	*4.30*	*4.96*	*4.66*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
Wind for public use (P.U.)	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.53*
CSP for domestic use (D.U.)	*0.68*	*0.68*	*0.68*	*0.68*	*0.04*	*0.04*	*0.04*	*0.04*	*0.04*	*0.00*
CSP for public use (P.U.)	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.68*
CSP for lighting of roads & squares (L.R.S.)	*0.00*	*0.00*	*0.00*	*0.00*	*0.63*	*0.63*	*0.63*	*0.63*	*0.63*	*0.00*
Energy recovery from MSW for domestic use (D.U.)	*0.36*	*0.38*	*1.00*	*0.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*0.36*
Energy recovery from MSW for lighting of roads & squares (L.R.S.)	*0.63*	*0.62*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.63*
Sum	***26.02***	***25.30***	***25.95***	***25.02***	***12.52***	***14.77***	***17.02***	***19.27***	***21.52***	***23.77***

*The share of each variable for each examined case (e.g. Optimal, *Bio-0.2*, *PV-0.9*, etc.) is shown in the above table. The sum shows the overall coverage percentage.

Table A3
Economic results for the examined scenarios.

	SCE_1 ***Opt***	SCE_2 ***Bio0.2***	SCE_3 ***PV0.9***	SCE_4 ***MSW0***	SCE_5 ***WF0.4***	SCE_6 ***WF0.5***	SCE_7 ***WF0.6***	SCE_8 ***WF0.7***	SCE_9 ***WF0.8***	SCE_10 ***WF0.9***	SCE_11 ***OptWFOff0.4***	SCE_12 ***OptWFOff0.6***	SCE_12 ***OptWFOff0.8***
Cost per KW	2168.05462	2′158.58	2′188.35	2′002.81	2′563.91	2′450.02	2′365.03	2′299.18	2′247.26	2′203.70	2′917.66	3′305.40	3′701.70
Capacity [MW]	1743.181316	1′717.80	1′810.57	1′670.97	862.83	1′009.51	1′156.18	1′302.86	1′450.26	1′596.50	1′698.73	1′677.49	1′656.88
GWh produced	4755.10	4′623.53	4′742.77	4′572.55	2′288.12	2′699.29	3′110.45	3′521.61	3′932.78	4′343.94	4′755.10	4′755.10	4′755.10
Net operating hours	2727.83	2′691.55	2′619.50	2′736.47	2′651.88	2′673.87	2′690.28	2′702.99	2′711.78	2′720.91	2′799.22	2′834.65	2′869.91
Project cost [MEUR]	3′779.31	3′708.00	3′962.15	3′346.63	2′212.21	2′473.31	2′734.41	2′995.50	3′259.11	3′518.22	4′956.30	5′544.79	6′133.28
Subsidy [MEUR]	755.86	741.60	792.43	669.33	442.44	494.66	546.88	599.10	651.82	703.64	991.26	1′108.96	1′226.66
Debt [MEUR]	2′078.62	2′039.40	2179.18	1′840.65	1′216.72	1′360.32	1′503.92	1′647.53	1′792.51	1′935.02	2′725.96	3′049.63	3′373.31
Equity [MEUR]	944.83	927.00	990.54	836.66	553.05	618.33	683.60	748.88	814.78	879.55	1′239.07	1′386.20	1′533.32
Interest rate	7.30%	7.30%	7.30%	7.30%	7.30%	7.30%	7.30%	7.30%	7.30%	7.30%	7.30%	7.30%	7.30%
NPV [MEUR]	2′635.31	2′511.58	2′558.55	2′667.20	1′481.08	1′676.62	1′870.30	2′062.74	2′256.21	2′444.80	2′030.46	1′715.08	1′395.94
Project IRR	11.59%	11.04%	10.17%	14.39%	10.77%	11.01%	11.19%	11.33%	11.44%	11.52%	4.00%	1.48%	-0.56%
Period payback (Yrs)	11	11	12	8	12	11	11	11	11	11	16	19	99

5. Conclusions

This concept of combined use of linear programming and techno-economic analysis imposes new views on the indagation process for the optimal solution. It was clearly proved that the optimal energy utilization scenario is not always the optimal scenario when approaching the implementation especially for the society. This analysis could be considered as a society-based optimization analysis aiming at taking advantage of the cost/efficiency-based optimization results and investigating which of

the proposed scenarios could also include the profitability of the project.

The methodology developed used a method of systemic analysis (definition problem → multi-objective modeling → optimal solution → various deterministic models for the operational parameters → techno-economic analysis → project sustainability). It was proved that the initial optimal solution was not at the same time the most economic for the society and at the same time the most profitable for investors. Therefore, another solution was chosen – the *MSW0* scenario – which cannot cover up to 26.02% of the energy needs of the city of Athens as in the *Opt* solution, but can cover approximately up to 25% (only 1% less), combining though economic planning and profitability for the companies involved.

Table A4
Variables used in the model.

Variable [%]	**Source of energy for end-use**
X_1	Solar thermal collectors for domestic use (D.U.)
X_2	Solar thermal collectors for agricultural use (A.U.)
X_3	PV for domestic use (D.U.)
X_4	PV for commercial use (C.U.)
X_5	PV for industrial use (I.U.)
X_6	PV for agricultural use (A.U.)
X_7	PV for public use (P.U.)
X_8	PV for lighting of roads & squares (L.R.S.)
X_9	Biomass for domestic use (D.U.)
X_{10}	Biomass for commercial use (C.U.)
X_{11}	Biomass for industrial use (I.U.)
X_{12}	Biomass for agricultural use (A.U.)
X_{13}	Biomass for public use (P.U.)
X_{14}	Biomass for lighting of roads & squares (L.R.S.)
X_{15}	Geothermal for domestic use (D.U.)
X_{16}	Geothermal for commercial use (C.U.)
X_{17}	Geothermal for industrial use (I.U.)
X_{18}	Geothermal for agricultural use (A.U.)
X_{19}	Geothermal for public use (P.U.)
X_{20}	Geothermal for lighting of roads & squares (L.R.S.)
X_{21}	Wind for domestic use (D.U.)
X_{22}	Wind for commercial use (C.U.)
X_{23}	Wind for industrial use (I.U.)
X_{24}	Wind for agricultural use (A.U.)
X_{25}	Wind for public use (P.U.)
X_{26}	Wind for lighting of roads & squares (L.R.S.)
X_{27}	CSP for domestic use (D.U.)
X_{28}	CSP for commercial use (C.U.)
X_{29}	CSP for industrial use (I.U.)
X_{30}	CSP for agricultural use (A.U.)
X_{31}	CSP for public use (P.U.)
X_{32}	CSP for lighting of roads & squares (L.R.S.)
X_{33}	Hydro for domestic use (D.U.)
X_{34}	Hydro for commercial use (C.U.)
X_{35}	Hydro for industrial use (I.U.)
X_{36}	Hydro for agricultural use (A.U.)
X_{37}	Hydro for public use (P.U.)
X_{38}	Hydro for lighting of roads & squares (L.R.S.)
X_{39}	Energy recovery from MSW for domestic use (D.U.)
X_{40}	Energy recovery from MSW for commercial use (C.U.)
X_{41}	Energy recovery from MSW for industrial use (I.U.)
X_{42}	Energy recovery from MSW for agricultural use (A.U.)
X_{43}	Energy recovery from MSW for public use (P.U.)
X_{44}	Energy recovery from MSW for lighting of roads & squares (L.R.S.)

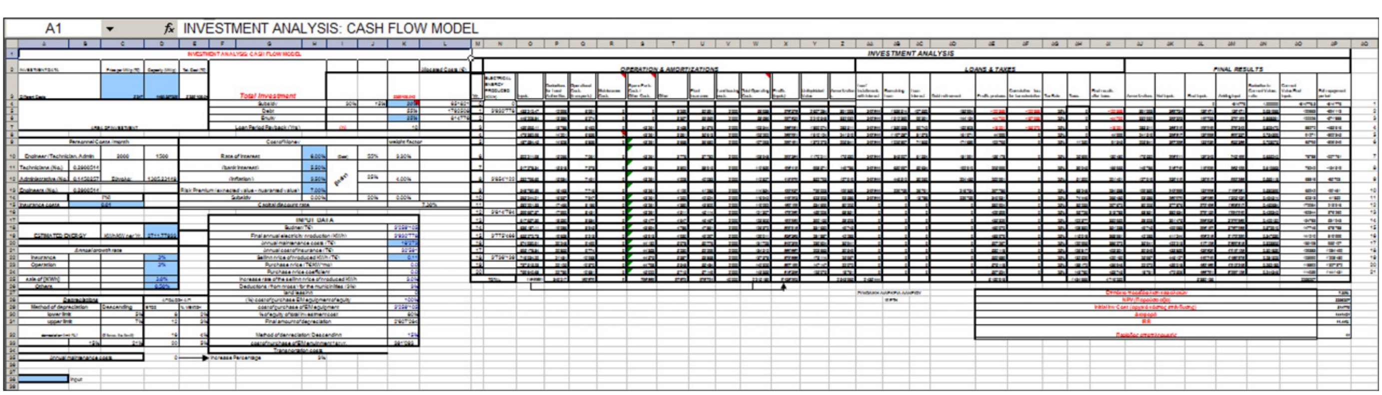

Fig. B1. Free Excel-based investment analysis model. Available from: http://www.uest.gr/ppt/investment_analysis_gxydis.xls

Appendix A

(See Tables A1–A4).

Appendix B

(Fig. B1).

List of various Assumptions on the Examined Scenarios:

Investment Scheme:

- Equity: 25%,
- Loan (Debt): 55%,
- Subsidy: 20%

Capital discount rate: 7.30%,
Inflation rate: 3.50%,
Loan period payback (in years): 10,
Rate of interest: ~6.00%,
Insurance costs: 0.01%,
Annual growth rate of insurance, operation, and KWh price: 3.00%,
Method of depreciation: descending 15%,
Deductions for local authorities (e.g. Municipalities): 3.00%,
Land leasing costs: estimated from market prices
Taxation: 25%
kWh selling price: based on the law N0.3851/2010.

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